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MRR Analysis on Technology of Piezoelectric Self-adaptive Micro-EDM

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Abstract

Micro electrical discharge machining (micro-EDM) has some shortcomings such as poor material removal rate and high electrode wear ratio etc. In order to overcome these demerits, a new piezoelectric self-adaptive micro-EDM, based on inverse piezoelectric effect, was developed in this paper. Piezoelectric actuator is used as the micro driving part. The working mechanism of this new technology is different from traditional micro-EDM. This new technology can realize self-elimination of short circuits in the working process because of its special structure. Working mechanism and process of the new system were illustrated. An empirical mathematical model on single-pulse discharge crater diameter against the key machining parameters was developed through partial least squares (PLS) regression to quantitatively disclose the discharge mechanism of this new technology. The effects of parameters such as voltage, capacitance, and resistance on MRR were analyzed. The empirical model represents good fits with the experimental data.

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Keywords: Piezoelectric actuator; Micro-EDM; MRRIntroduction

1. Introduction

Electrical discharge machining (EDM) is a non-traditional concept of machining, which has many advantages, including the fact that the machining process is independent of the hardness of workpiece,

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and the machining force exerted on workpiece is much lower than in mechanical machining process[1,2]. Compared with conventional micro-fabrication techniques, EDM can machine three-dimensional complex microcomponents and microstructures from metallic substrate and semiconductor substrate, and it can machine small holes with high aspect ratio easily [3,4]. Consequently, it has become one of the most important methods for machining micron and submicron components.

There is no essential difference in machining mechanism between micro-EDM and normal EDM, both are thermal process employing electric-thermal energy to remove material from the selected areas, but micro-EDM has some special characteristics because of the micro scale [5,6]. For example, the material removal rate (MRR) is poor and electrode wear ratio (EWR) is great, etc. In order to overcome the shortages of micro-EDM, a new method based on inverse piezoelectric effect of piezoelectric ceramic was presented, and detailed research on experiments was processed in this paper.

2. Working mechanism of Piezoelectric Self-adaptive Micro-EDM

The structural design and working mechanism of the new device are different from the conventional micro-EDM devices. Fig.1 shows the mechanism of piezoelectric self-adaptive micro-EDM technology. Piezoelectric actuator is jointed to the macro-driven table and serves as the main adjuster to maintain stable machining because of the higher frequency response. The resonant frequency of the piezoelectric actuator is 10 kHz, and the resolution is 0.45nm. The macro-driven table can feed forward with macro step and the resolution is 1 μ m. The DC power is connected not only with piezoelectric actuator but also with the tool electrode and workpiece, thus makes up a parallel circuit. This circuit forms an equivalent RC circuit because the piezoelectric actuator can be regarded as a capacitor. The capacitance of the piezoelectric actuator is invariant and its equivalent capacity is 4.5 μ F, in order to adapt different machining criteria, an adjustable capacitor is parallel connected with the piezoelectric actuator, the equivalent circuit is shown in Fig. 2. C_1 is piezoelectric actuator, C_2 is an adjustable capacitor. A resistance R_2 is series with the piezoelectric actuator in discharging circuit to protect the piezoelectric actuator from damage because of heavy current. At the same time, this resistance R_2 can change the following effect of piezoelectric actuator to ensure that the machining process is always in optimum condition.

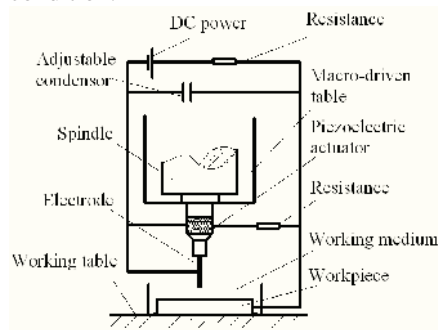


Fig.1 Schematic diagram of working principle

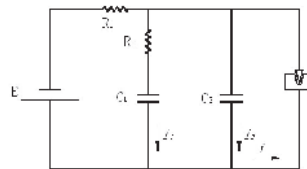


Fig. 2 Equivalent-circuit diagram

The working process of piezoelectric self-adaptive micro-EDM system is: first, the piezoelectric actuator C_1 and adjustable capacitor C_2 are charged by a DC power whose voltage can be regulated continuously from 0V to 100V, the piezoelectric actuator stretches forward because of the increase of its voltage; second, the macro driving table drives the piezoelectric actuator and electrode move forward, when the gap between electrode and workpiece achieves a suitable breakdown gap for discharging, the

discharge channel is formed, the capacitor C_2 and piezoelectric actuator C_1 discharge instantaneously at the same time. The piezoelectric actuator retracts because of the sudden fall of voltage, and electrode moves backward with the piezoelectric actuator, the gap between electrode and workpiece becomes bigger and bigger, the discharging will be broken down and a discharge is completed; the capacitor C_2 and piezoelectric actuator C_1 will be charged again by the DC power soon after, the piezoelectric actuator protracts once more, when the gap between electrode and workpiece achieves a breakdown value for discharging, a second discharging occurs. Thus, piezoelectric self-adaptive EDM will be implemented.

When short circuits turn up, the voltage of piezoelectric actuator declines rapidly, simultaneously, the piezoelectric actuator contracts quickly and drives the electrode to retract until the short-circuit condition is eliminated. Subsequently, piezoelectric actuator will be recharged and discharge turns up when discharge gap reaches the suitable value, the discharge processing is keeping on. So this new technology can realize self-elimination of short circuits in the working process.

3. Analysis of discharge energy

$$i = i_1 + i_2 = C_1 \frac{du_{C_1}}{dt} + C_2 \frac{du_{C_2}}{dt} \quad (1)$$

During EDM process, the material of the electrodes is removed through the thermal erosion of discharge energy. In the discharging circuit shown in Fig. 2, ignoring the impact of power on the discharge process, the total current i , that is, the discharge current is equal to the sum of the discharge current i_1 of C_1 and the discharge current i_2 of C_2 , namely:

Where, u_{C_1} is the voltage of piezoelectric actuator C_1 and u_{C_2} is the voltage of adjustable capacitor C_2 .

The single pulse discharge energy of this system can be derived:

$$\begin{aligned} W &= \int_0^t u(t)i(t)dt \\ &= \int_0^t u_{C_2} \left(C_1 \frac{du_{C_1}}{dt} + C_2 \frac{du_{C_2}}{dt} \right) dt \\ &= \int_0^t U e^{-\frac{t}{rC_2}} \left[C_1 \frac{d \left(U e^{-\frac{t}{(r+R_2)C_1}} \right)}{dt} + C_2 \frac{d \left(U e^{-\frac{t}{rC_2}} \right)}{dt} \right] dt \\ &= U^2 \left[\frac{C_2}{1 + \frac{R_2}{r} + \frac{C_2}{C_1}} \cdot e^{-\left(\frac{1}{rC_2} + \frac{1}{(r+R_2)C_1} \right)t} + \frac{C_2}{2} \cdot e^{-\frac{2t}{rC_2}} \right] \Big|_0^t \end{aligned} \quad (2)$$

Where, U is the open voltage, t is the discharge duration of a single discharge and r is the resistance of discharge gap.

Normally, it can be considered that the capacitor is fully discharged when $t=5rC_2$. So it can be obtained from (2):

$$W = \frac{1}{1 + \frac{R_2}{r} + \frac{C_2}{C_1}} C_2 U^2 + \frac{1}{2} C_2 U^2 \quad (3)$$

In (3), the resistance in discharge gap is very small, commonly less than 1Ω . However the value of the resistance R_2 is very high and it is over than 510Ω generally. $R_2/r \gg 1$, therefore, (3) can be simplified as following:

$$W \approx \frac{1}{2} C_2 U^2 \quad (4)$$

4. Process modeling

4.1. Empirical model of single-pulse discharge diameter

During the micro-EDM process, the material is removed by means of repetitive spark discharges. With each discharge, a small crater is formed on the machined surface. The topology features of the single pulse discharge crater are helpful to disclose the discharge mechanism, and also can disclose relationship between machining parameters and machining performances, such as the material removal rate, surface roughness, etc. Therefore, it is significative to investigate the intrinsic relations between geometric feature of the single-pulse discharge crater and machining parameters.

According to the machining mechanism EDM, the shape of single-pulse discharge crater is a spherical crater. The average diameter and depth of the spherical crater, as main characteristic geometrical dimension of the crater, are D and H . Limited to measurement means, only the diameter D of single-pulse discharge crater can be obtained. H can be calculated according to the relationship between H and D which has been proved through many experiments, and in general H/D is about 0.1-0.2 [7].

Empirical models possess simple and easy-to-get characteristics, and usually give good correlation for the range in which the equations are determined if all of the important variables have been taken into account. The diameter of crater is main dependent on the discharge energy. According to (4), the discharge energy of this new technology is mostly supplied by C_2 . So the empirical model can be expressed as follows:

$$D = K C_2^a U^b \quad (5)$$

Where K is constant coefficient a, b are the exponent value of C_2, U .

The unknown model parameter can be determined with the aid of regression analysis methods on the basis of measured data. In regression, the predictors do not have to be normally distributed, linearly related, or of equal variance within each group. The complex non-linear problems can convert to a linear form via a suitable transformation.

Hence, (5) can be linearized by taking logarithmic transforms as follows:

$$\ln D = \ln K + a \ln C_2 + b \ln U \quad (6)$$

Based on the partial least squares (PLS), MINITAB standard version software has been used to estimate the parameters of the above model, the data as shown in Table 1.

The developed empirical model for D is given below:

$$D = 0.186 C_2^{0.357} U^{0.836} \quad (7)$$

Every input variable with a P-value less than 0.001 are considered to have a statistically significant contribution to the performance measures. The predicted D for each set of experiment has been calculated using (7) and the actual experimental values and predicated values of D have been compared to verify the closeness between measured and predicated values. The range of maximum deviation in predicted error percentage for D is from 0.05% to 8.77% respectively which validates the developed empirical model.

Table 1 Empirical model validation.

Test No.	C ₂ (nF)	U (V)	D Test value (μm)	D Predicted value (μm)	Error (100%)
1	10	30	7.14	7.28	1.96
2	10	40	9.00	9.26	2.92
3	10	50	10.71	11.16	4.18
4	10	60	12.43	13.00	4.59
5	10	70	13.86	14.79	6.71
6	33	30	11.14	11.15	0.05
7	33	40	14.86	14.18	4.56
8	33	50	18.57	17.09	8.00
9	33	60	21.29	19.90	6.51
10	33	70	24.29	22.64	6.79
11	100	30	16.57	16.55	0.10
12	100	40	21.14	21.05	0.42
13	100	50	25.71	25.37	1.33
14	100	60	31.00	29.55	4.68
15	100	70	35.43	33.61	5.13
16	1000	30	37.29	37.63	0.92
17	1000	40	44.57	47.86	7.38
18	1000	50	54.57	57.67	5.68
19	1000	60	62.14	67.17	8.08
20	1000	70	71.57	76.40	6.75
21	3300	30	63.14	57.60	8.77
22	3300	40	67.71	73.26	8.19
23	3300	50	86.29	88.28	2.32
24	3300	60	95.86	102.82	7.26
25	3300	70	120.00	116.96	2.54
26	10000	30	81.71	85.54	4.68
27	10000	40	116.86	108.79	6.90
28	10000	50	143.29	131.09	8.51
29	10000	60	158.43	152.68	3.63
30	10000	70	172.57	173.67	0.64

4.2. Analysis of MRR

In order to derive the models for the new technology, the following assumptions are put forward:

(1) The micro-EDM process is carried out through a series of pulses and there is only one spark every pulse.

(2) The shape of the crater formed by a single spark in the new micro-EDM is spherical crater.

(3) All effective discharge voltage waveforms are the same.

(4) The ignition delay time is very short compared with the discharge time.

(5) The machining process is continuous.

Base on the above assumptions and (7), the volume of crater can be depicted as following:

$$V_s = \eta' (0.186 C_2^{0.357} U^{0.836})^3 = \eta_1 C_2^{1.071} U^{2.508} \quad (8)$$

Where V_s is volume of crater, that is, volume of material removed by a single spark and η_1 is the proportional constant.

The total material removed V_{tot} is the summation of the volume of the material removed by all single sparks:

$$V_{tot} = \sum_{s=1}^n V_s = n V_s = n \eta_1 C_2^{1.071} U^{2.508} \quad (9)$$

Each spark cycle, T_s , is given by

$$T_s = T_{on} + T_{off} \quad (10)$$

Where, T_{on} is pulse on time and its value is about $(3 \sim 5) R_1 C_2$; T_{off} is pulse off time, its value is about $5r C_2$. Where R_1 is resistance of charging circuit and C_2 is capacitance of adjustable condenser; r is resistance of the discharging circuit.

The total time of micro-EDM process is

$$T_{tot} = \sum_{s=1}^n T_s = n T_s \quad (11)$$

The material removal rate (MRR) is defined by

$$MRR = \frac{V_{tot}}{T_{tot}} \quad (12)$$

Substituting (9), (10) and (11) into (12). It can give

$$MRR = \frac{n \eta_1 C_2^{1.071} U^{2.508}}{n [(3 \sim 5) R_1 C_2 + 5r C_2]} = \eta \frac{C_2^{0.071} U^{2.508}}{(3 \sim 5) R_1 + 5r} \quad (13)$$

Where η is proportional constant, C_2 is the capacitance of adjustable capacitor, U is the open voltage, R_1 is the resistance of charging circuit and r is resistance of discharging circuit.

5. Experimental results and discussions

Experiments were carried out to show the effects of open voltage, capacitance, resistance R_1 and R_2 on the MRR. The electrode is copper whose diameter is 0.1mm, and the workpiece is stainless steel whose thickness is 0.1mm, and it is anode in the experiment. The detailed experimental variables are summarized in table 2.

Table 2 Summary of experimental condition

Test No.	Open voltage U (V)	Capacitor C_2 (pF)	Resistance R_1 (Ω)	Resistance R_2 (Ω)
1	30,40,50,60,70	1000	200	510
2	50	100,390,1000,2200,4700	200	510
3	50	2200	200,510,1000,2000	510
4	50	2200	200	200,510,1000,2000,5100

5.1. The effect of open voltage on MRR

The results show that the MRR tends to increase with the increase of open voltage, as shown in Fig. 3. The reason is that the capacitance energy increases with the increase of open circuit voltage, leading to the increase of single pulse discharge energy, which improves the MRR. The curve trend coincides with the (13).

5.2. The effect of capacitance C_2 on MRR

As can be seen from the Fig. 4, MRR increases with the increase of capacitance, and the tendency is coincides with the (13). This is because the capacitance is also a main factor impacts the single discharge energy in RC-circuit. The increase of capacitance results in the increase of single pulse discharge energy which can produce more heat. So the MRR will increase with the increase of capacitance.

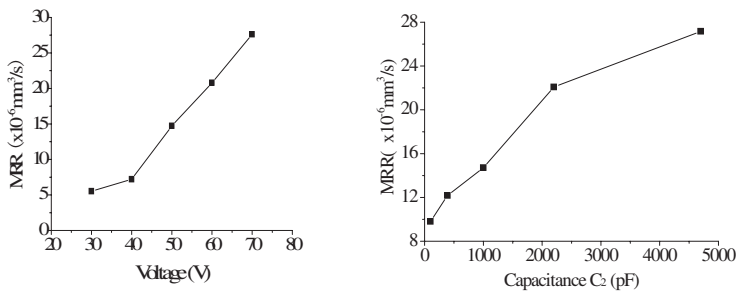


Fig. 3 Effect of open voltage on MRR Fig. 4 Effect of capacitance on MRR

5.3. The effect of Resistance R_1 on MRR

As depicted in (13), it is an inverse relationship between MRR and R_1 , that is, MRR will decrease with the increase of R_1 . While in the Fig. 5, the MRR increases at first and then becomes to decrease with the increase of resistance R_1 . The reason is that the pulse off time is so small during the working process that

heat in the discharge channel has no enough time to dissipate when the resistance R_1 is small, and discharge would be reignited at the same place, further increasing the local temperature, which is likely to cause abnormal arc resulting in the small value of MRR. With the increase of resistance R_1 , the pulse off time will increase, the heat has enough time to dissipate and machined debris can be removed effectively, so the unstable discharge phenomenon will decrease which makes the MRR increase. But after a certain value, with the increase of R_1 , the charge time of capacitance will increase greatly, which causes the MRR decrease.

5.4. The effect of Resistance R_2 on MRR

There is no R_2 in (13), while R_2 has some effect on MRR as shown in the Fig. 6. This is because that when the (13) is deduced, it is assumed that the process is normal, that is the R_2 is in optimal value, which makes the piezoelectric actuator in the best following effect.

The MRR will decrease according to a certain trend with the increase of resistance R_2 . The main reason is that when the resistance R_2 is small, the discharge current of piezoelectric actuator i_1 will increase, which cause the discharge current of the discharge gap i increase, resulting in the increase of the single discharge energy, which causes the high MRR. Then with the increase of resistance R_2 , discharge current provided by piezoelectric actuator becomes smaller and smaller, so the MRR decreases. When the resistance R_2 reaches a certain value, the discharge energy will become stable, and almost no change in it with the change of resistance R_2 . However, continuous increase of resistance R_2 causes the tardiness of following effect of piezoelectric actuator, which could increase the frequency of abnormal discharges, resulting in decrease of the MRR.

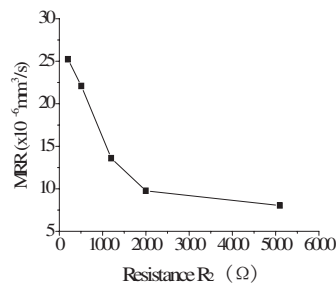
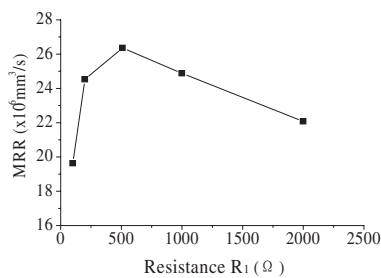


Fig. 5 Effect of resistance R_1 on MRR Fig. 6 Effect of resistance R_2 on MRR

6. Experimental examples

Experiments have been done with this new technology. Electrode is $\phi 0.1\text{mm}$ Cu, workpiece is stainless steel with the thickness 0.1mm and it is anode in the experiment. The parameters are: $E=70\text{ V}$, $R_1=510\ \Omega$, $R_2=510\ \Omega$, $C_2=4700\text{ pF}$. In the processing, the machining is continuous. After 40s, the electrode proceeds $180\mu\text{m}$, and the wear length of electrode is about $36\mu\text{m}$. Fig. 7 is the small hole machined on stainless steel with this technology.

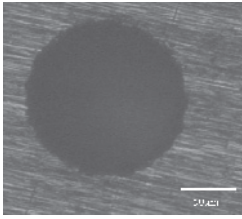


Fig. 7 Small hole on stainless steel

7. Conclusions

The principle of piezoelectric self-adaptive micro-EDM has been introduced and the effect on MRR has been measured. Based on the discussions above, following conclusions can be drawn:

- 1) The open voltage has greater effect on MRR because the increase of open voltage will cause the single discharge energy increase greatly.
- 2) The MRR will rise with the increase of capacitance of C_2 because the increase of capacitance results in increase of single discharge energy.
- 3) With the increase of resistance R_1 , the MRR will increase firstly and then becomes to decrease.
- 4) With the increase of resistance R_2 , MRR will decrease because of tardiness of following effect of piezoelectric actuator.

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